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IMPROVEMENT IN CRACK DETECTION BY ULTRASONIC PULSE-ECHO WITH LOW FREQUENCY EXCITATION

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ABSTRACT

A program of analytical and experimental research was conducted to investigate the effect of stress fields on the ultrasonic energy reflected from thin flat cracks in solids. It was established that the intensity of ultrasonic echo signals is decreased by compressive stress and increased by tensile stress; the effect being maximum when the stress acts normal to the crack plane. Thus a crack in compression is more difficult to detect with ultrasonic pulse-echo techniques than is an unstressed crack. Improvement in detection is obtained by application of tensile stress. It was determined that the change in echo intensity with applied stress is related to the change in effective crack opening, which in turn is a function of the stress intensity at the crack tips. For this response to occur, the initial opening of a crack must be within a critical range of values. This critical range is a function of acoustic impedance mismatch at the crack interface and the frequency of the ultrasonic input pulse.

The results of studies to determine the feasibility of inducing stress in metal samples with low frequency excitation have indicated that the effective use of this technique is limited to excitation in the cyclic frequency range of 1000 Hz and below. Best results were obtained with solid coupling of low frequency exciters to test material. Attempts to induce stress with excitation at 20 kHz were not very successful with the techniques and equipment used in these studies.

The potential of the information acquired for use in NDT practice is discussed, and some examples of possible benefits are presented.

FOREWORD

This report is the final [redacted] report on the studies to improve the detectability of closed cracks with ultrasonic pulse-echo techniques. The research program is sponsored by the Advanced Research Projects Agency of the Department of Defense and is monitored by the Naval Ship Research and Development Laboratory under Contract No. N00140-70-C-0223. Mr. Charles Zanis is Technical Monitor.

The program was conducted in the Materials Science Laboratory of the Syracuse University Research Corporation under the direction of Mr. John G. Sessler, Principal Investigator, assisted by Dr. Volker Weiss, Professor of Metallurgy at Syracuse University. Mr. Mukul Sengupta, graduate student candidate for masters' degree in the Department of Chemical Engineering and Metallurgy, and Mr. Leland Barrus, NDT and electronic technician, have also participated in the program.

This report covers the period from 28 October 1969 to 27 October 1970.

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I. INTRODUCTION

The Materials Science Laboratory of the Syracuse University Research Corporation (SURC-MSL) has conducted an analytical and experimental research program to investigate the effect of stress fields on the amount of ultrasonic energy reflected from thin flat cracks in solids. The program was initiated in response to a need for improvement in the detection of this type of crack which has proven to be difficult to detect by available non-destructive testing (NDT) techniques. The detection of thin cracks is known to become even more difficult when the crack is located in a compressive stress field.

One of the available NDT methods that is widely used for the detection of cracks (and also other types of flaws) is the ultrasonic pulse-echo technique. The ultrasonic pulse-echo systems presently available for commercial testing are quite versatile and are extremely sensitive to small amounts of ultrasonic reflected energy. In the case of the tightly closed crack, however, the amount of energy reflected may be less than the resolving capability of the system if the impedance mismatch at the crack interface is reduced to very low values. This situation can occur if the contact area along the interface between crack surfaces is increased by the presence of compressive stress (e.g. applied or residual) normal to the plane of the crack.

The difficulty in detecting thin cracks by pulse-echo may be understood more clearly by giving attention to relationships proposed by Lord Rayleigh in 1877, (1). Based on acoustic wave theory, Rayleigh derived an equation to predict the intensity of acoustic waves reflecting from a thin film of a given media (media 2), when the thin film is located between media (media 1) different than that of the film. Rayleigh's equation for the percentage of incident energy reflected from a thin film at normal incidence is given bv:

$$I_r/I_i = \frac{\left(\frac{Z_1}{Z_2} - \frac{Z_2}{Z_1}\right)^2}{\left(\frac{Z_1}{Z_2} + \frac{Z_2}{Z_1}\right)^2 + 4\cot^2\left(\frac{2\pi t}{\lambda}\right)} \qquad \text{Equation 1}$$

where

Z_1 = acoustic impedance of first media

Z_2 = acoustic impedance of thin film

t = thickness of film

λ = wavelength of sound in second media (thin film)

In effect, Equation 1 states that the intensity of acoustic waves reflecting from thin films is not only a function of acoustic impedance mismatch at the interface, but is also influenced by film thickness.

Relating this equation to a thin air gap (e.g. crack) in solids, the existence of a critical crack opening is predicted and, for crack openings less than the critical value, the intensity of echoes reflected from the crack is reduced. Thus if a crack is thin, and its opening is less than a critical amount, the crack may be difficult to detect by pulse-echo. On the other hand, it follows that if the opening is increased to the critical value (or larger), then the intensity of reflected signal is increased and detection of the crack is enhanced.

Crack opening can be increased by the application of tensile stress in a direction normal to the plane of the crack. Using linear elastic fracture mechanics (2), the amount of crack opening displacement can be calculated as a function of tensile stress in the crack region. Solutions are available for several crack geometries including parabolic and elliptical shaped cracks. Using the principles discussed above, it appears possible to obtain improvement in the detection of thin cracks in solids by introducing tensile stress in the crack region to increase the crack opening. Theoretical calculations indicate that if a thin crack can be opened a small amount (in the order of a few microinches), it should be more easily detected by ultrasonic reflection techniques. The stress required for opening a crack can be introduced by applying external static forces. In the SURC-MSL program, serious consideration was also given to the possibility of providing the required stress by means of low frequency excitation, since this method appeared to have some advantages over the application of static loads.

The major objectives of the research program were as follows:

Phase I To determine the effect of tensile and compressive stress fields on the amount of ultrasonic energy reflected from thin flat cracks in solid materials.

Phase II To explore the feasibility of inducing stress in the region of thin cracks in solids by application of low frequency excitation.

The program was conducted over a period of two years. In the first year of the program, it was determined that the amount of energy reflected from a thin crack by ultrasonic pulse-echo was very sensitive to small changes in stress intensity at the crack tips, (3). It was observed experimentally that the amount of reflected energy is decreased by compressive stress and increased by tensile stress, and that the effect is maximum when the stress is applied in a direction normal to the crack plane. Thus a crack in compression is more difficult to detect than an unstressed crack. On the other hand, the detection of thin cracks is enhanced by applying tensile stress to increase the stress intensity at the crack tips.

Also, in the first year of the program, experimentation was initiated to explore the feasibility of inducing stress in the region of a thin crack by means of low frequency excitation. In principle, this technique is to induce a stress field in the vicinity of a crack by introducing sound vibrations of sufficient acoustic intensity to provide the required stress, while simultaneously searching for the crack with ultrasonic pulse-echo flaw detection methods. The results of the first years' effort indicated that it is technically possible to induce a cyclic stress field in the region of cracks with low frequency excitation, and that inducing stress by this technique can enhance the detection of thin cracks by pulse-echo. The effect produced experimentally, however, was relatively small and the potential usefulness of the technique in NDT practice was not established at that time, (3).

In the second year of the program further experimentation and analyses pertinent to the objectives of Phase I and Phase II of the program were conducted, and the results of these efforts are reported and discussed herein. In addition, a third phase was initiated to combine ultrasonic techniques with fracture mechanics analyses as a means to provide improvement in characterizing the size and severity of cracks detected in solids. The Phase III studies were directed towards utilizing the relationships between stress intensity at crack tips, crack opening displacement (COD) and ultrasonic energy reflected from the crack interface to improve the accuracy in determining true crack size. The analyses developed in the Phase III studies, and the experimentation performed to evaluate the behavior of cracks in terms of the proposed analyses, have provided the basis for a Masters thesis, now in preparation. The thesis is being prepared by Mr. Mukul Sengupta, graduate student in the Department of Chemical Engineering and Metallurgy at Syracuse University. It is planned that, upon completion, the information contained in the thesis will be presented in an Interim Technical Report.

II. TECHNICAL SUMMARY

The objective of the research program was to investigate the effect of stress fields on the ultrasonic energy reflected from thin flat cracks in solids for the purpose of utilizing this effect for improvement in the detection of this type of crack. The studies consisted of analyses and experimentation to evaluate the effect of stress and crack opening displacement on the amplitude of ultrasonic echo signals for cracks of various sizes in steel. In these studies, tensile and compressive stresses were introduced in a direction normal to the plane of the crack by static loading (Phase I) and also by the application of low frequency excitation to the test specimens (Phase II).

The results obtained in Phase I of this program, together with the results of earlier studies (3), show that the amplitudes of echo signals reflecting from thin cracks in steel are decreased when compressive stress is applied to the crack and are increased by tensile stress. Thus a crack in a compressive stress field is more difficult to detect by ultrasonic pulse-echo techniques than an unstressed crack. Further, the results show that improvement in detection is obtained by applying tensile stress to the crack. Qualitatively it has been shown that factors pertinent to the observed effects include (a) the characteristics of the ultrasonic instrumentation, (b) the characteristics of the material containing the crack and (c) the geometry of the crack. Analyses of the test results have also shown that the effect of stress on ultrasonic energy reflected from thin cracks is related to the change in crack opening, which in turn is related to the change in stress intensity at the crack tip. It is proposed that the information acquired in this program can be utilized in NDT practice, provided that the basic principles are well understood. A discussion of possible practical applications of these principles is presented in Section VI.

The techniques employed, the problems encountered and the results obtained in the studies to induce stress in a steel sample with low frequency excitation are discussed in Section III, Phase II, and in Section IV. Based on the data obtained in this program under optimized conditions, it appears that the use of low frequency exciters to induce stress in metal samples with moderate power is limited to the cyclic frequency range of 1000 Hz and below. In general, the test results indicated that the stress induced in this range of frequencies was proportional to the effective force transferred to the test specimen from the exciter. Transfer was best accomplished with solid coupling of exciter to specimen. A greater effect was observed when the exciter frequency was tuned to the natural frequency of the system.

Attempts to induce stress with higher frequency excitation (e.g. 20 kHz) were not very successful. Considerable difficulty was encountered in detecting changes in echo amplitude at this frequency, and efficiency of transfer of energy from transducer to specimen was quite low. Some improvement was obtained by driving the 20 kHz transducer with a lower frequency exciter. It was judged, however, that this technique did not appear to be feasible for providing improvement in the detection of cracks in NDT practice.

III. TECHNICAL PROGRAM

A. Phase I

Phase I of the program was concerned with investigating the effect of tensile and compressive stress fields on the amount of ultrasonic energy reflected from thin flat cracks in solid materials. Postulating that thin cracks are analogous to thin films in solids, the relationship derived by Rayleigh (Equation 1) can be useful in evaluating the effect of stress. Equation 1 predicts that a change in the intensity of reflected waves will occur with a change in crack opening, if the original crack opening is less than some critical value. The relationship between crack opening and intensity of reflected waves is dependent upon the acoustic impedance mismatch between the respective media involved, and also on the wavelength of sound in the media contained within the crack boundaries.

An illustration of the change in reflection that is predicted as a function of change in air film thickness (e.g. crack opening) is shown in Figure 1. In this case a thin film of air, enclosed in a steel matrix, is assumed to be located in the path of a 5 MHz ultrasonic beam at normal incidence and the percent reflection is calculated for various film thicknesses, according to Equation 1. Under these conditions, it is observed that a large change in reflection occurs in the range of film thickness from about 10^{-6} to 10^{-8} centimeters (1 to 100 Angstroms). This means that cracks with openings in this effective range would be expected to respond in a similar manner when the crack opening is varied from the initial opening. For comparison purposes, a curve calculated for a search unit frequency of 1.0 MHz also included in Figure 1. It can be seen that, at the lower frequency, the effective range of air film thickness shifts to higher values.

Crack openings can be changed by applying stress in the region of a crack. Therefore, the amount of ultrasonic energy reflected from thin cracks (whose openings are in the effective range) is expected to change with the magnitude of applied stress. This effect of stress on reflected energy was clearly demonstrated by experiments performed in the first year of the program on steel cantilever bend specimens containing natural (e.g. fatigue) cracks. The experimental techniques used for these tests were discussed in detail in Reference 3. A sample of the data obtained is shown in Figure 2, where the change in ultrasonic echo amplitude for a 5 MHz longitudinal beam is shown qualitatively as a function of applied tension and compressive stress.

Using linear elastic fracture mechanics analysis (2), it can be shown that the crack opening displacement (change in crack opening due to stress) is related to the stress intensity at the crack tip by

$$2\eta \text{ (COD)} = \frac{4K}{E\pi}\sqrt{2\pi x}\,(1-\nu^2) \qquad \text{Equation 2}$$

where K = stress intensity at crack tip

x = distance from crack tip along crack plane

E = Young's modulus

ν = Poisson's ratio

When η is small compared to x, as is the case for very thin cracks, then:

$$K = \sigma_a\sqrt{\pi a} \qquad \text{Equation 3}$$

where σ_a = gross section stress acting normal to the crack plane

a = length of an elliptical surface crack or half length of an elliptical enclosed crack

Substitution of Equation 3 in Equation 2 gives

$$2\eta = 5.66\sqrt{ax}\left(\frac{\sigma_a}{E}\right)(1-\nu^2) \qquad \text{Equation 4}$$

Maximum COD is obtained at the location where x = a, thus:

$$2\eta_{max} = 5.66\,a\left(\frac{\sigma_a}{E}\right)(1-\nu^2) \qquad \text{Equation 5}$$

The effect of gross section stress or stress intensity on reflected energy can be determined experimentally, provided that the influence of all factors pertinent to this relationship are well understood. Qualitatively it has been shown (3) that these factors include the characteristics of the ultrasonic instrumentation and the matrix material, as well as the crack geometry. When these factors are accounted for and can be adequately controlled, it appears that observed changes in amplitude of an ultrasonic signal (echo) reflected from a crack interface, as a function of known stress changes, can provide improvement in crack detection.

The ultrasonic instrumentation employed for the investigation was described in Reference 3. To evaluate the ultrasonic instrument parameters and obtain calibration curves for the systems employed in the investigation, a series of experiments were performed using a set of ultrasonic standard reference blocks containing flat bottom holes. These blocks were manufactured from 4340 alloy steel and were fabricated to the dimensions given in ASTM E127-64 for aluminum blocks (4). The set contained eight blocks, each block containing a flat bottom hole. The smallest and largest hole diameters were 1/64 and 8/64 inch, respectively. All holes were located at 3 inch metal travel depths in the steel blocks.

The area-amplitude calibration data obtained with a 5 MHz normal contact search unit is illustrated in Figure 3. In this graph the relative echo signal amplitude obtained from the holes is plotted versus relative area units. Reference setting was 40 percent signal height for the 5/64 inch hole. Figure 4 presents calibration data for search units of 2.25, 5 and 10 MHz, with sensitivity (gain setting) required for a 10 division echo signal shown as a function of reflecting area of the flat bottom holes. The effect of the Reflectoscope reject control setting is shown in Figure 5 for the 5 MHz search unit.

The effect of tensile and compressive stress fields on the ultrasonic energy reflected from thin cracks in steel and aluminum specimens, and the techniques employed to determine this effect, were presented in Reference 3. Additional data obtained on steel specimens is illustrated graphically in Figures 6, 7 and 8. In these graphs the change in echo amplitude is shown as a function of the stress intensity at the crack tips. Amplitude changes are given in terms of voltage changes (dV), as measured with the Graphigate signal output system of the Reflectoscope. These values are divided by gain setting (S) to normalize the data for the purpose of comparing the relative amount of energy reflected from cracks of different sizes. The curves in Figure 6 were obtained with a 2.25 MHz normal contact search unit, while the curves in Figures 7 and 8 were obtained with 5 and 10 MHz units, respectively. By comparing these curves, it can be seen that when the gain setting is normalized, the largest response to stress changes in the region of a crack was obtained with the 5 MHz search unit.

Experiments were conducted to determine whether the effect of stress on echo amplitude can also be measured with ultrasonic transverse (shear) waves. For this experiment, a 5 MHz shear (45° angle-steel) search unit was employed and measurements were taken on a steel specimen containing a fatigue crack 0.38 inch in length. Stress was applied in bending with the technique described previously in Reference 3. The data obtained are illustrated in Figure 9. Also included in this graph are the data obtained under identical conditions with a 5 MHz normal (longitudinal wave) search unit. It can be seen from Figure 9 that the effect of stress can be measured with shear waves; however, under the conditions employed in these tests, the response is less than that observed with longitudinal waves. In Figure 11 data is presented to show the effect of axial tensile stress on echo amplitude for two different conditions of signal reject. A comparison of the effect of bend stress and axial tension stress on echo amplitude is shown in Figure 12. These data indicate that the echo response is the same regardless of the type of loading, provided that stress intensity at the crack tip is the same in each case.

B. Phase II

The efforts in Phase II of the program were concerned with exploring the feasibility of improvement in the detection of tight cracks by means of low frequency sound excitation. In principle, the technique is to induce a stress field in the vicinity of a crack by introducing a sound beam of sufficient intensity to open the crack, while simultaneously searching for the crack with ultrasonic pulse-echo detection methods.

Preliminary calculati ns, using theory of elasticity and acoustic wave theories, suggested that the above described technique should be possible. The model chosen for these calculations was an unstressed flat elliptical crack, 0.25 inch in length, enclosed in steel with the plane of the crack located in a direction normal to the axis of a 5 MHz ultrasonic normal incident beam. According to Figure 1, if the crack has an initial opening in the range of 10^{-6} to 10^{-7} inch, a significant change in reflection coefficient will occur when the crack opening is increased. The amount of increase required (crack opening displacement) is predicted to be of the order of magnitude of 10^{-6} inch. From Equation 5, it is determined that a gross section tensile stress of about 50 psi or a stress intensity at the crack tip of about 30 psi$\sqrt{\text{inch}}$ is required to produce a maximum crack opening displacement of 10^{-6} inch. This relationship is illustrated in Figure 10 for cracks of various lengths from 0.001 to 1.0 inch. For these calculations, Young's modulus for steel was taken as 30 x 10^6 psi and Poisson's ratio as 0.3.

Tensile stresses, sufficient to provide the desired crack opening displacement, can readily be provided by application of either static or very low frequency (e.g. 60 Hz or less) dynamic forces coupled solidly to the sample. The purpose of the Phase II studies was to determine if sufficient stress could be induced by excitation in the range of frequencies from 1000 Hz to 20 kHz, and with contact rather than solid coupling. Excitation at 20 kHz would, in particular, be desirable because sound at this frequency is above the range audible to the human ear.

The maximum stress produced in a solid medium by introducing longitudinal waves of amplitude A and frequency f is given by

$$\sigma_{max} = 2\pi EA \frac{f}{V_L} = \frac{2\pi EA}{\lambda} \qquad \text{Equation 6}$$

where λ = wave length at frequency f

V_L = sound velocity of longitudinal waves in the solid media

According to Equation 6, the amplitude of vibration required to produce a stress of 50 psi in a steel sample with a sound beam of 20 kHz is 2.65 microinch. The power required to produce an acoustic vibration of amplitude A at frequency f is obtained as the product of acoustic intensity (I_a) and the area through which the acoustic energy flows. Acoustic intensity is expressed as

$$I_a = 2\rho V_L (\pi f A)^2 \qquad \text{Equation 7}$$

where ρ = density of the media

V_L = velocity of a longitudinal sound wave

From Equation 7, it can be calculated that an acoustic intensity of approximately one watt of acoustic power per square inch of cross-section is required to provide a vibration amplitude of 2.65×10^{-6} inch in steel at 20 kHz. Based on these calculations, it appeared worthwhile to investigate the feasibility of introducing stress in the region of a thin crack by means of acoustic excitation.

Four different types of vibration exciters were employed for the studies in Phase II. The characteristics of the exciters, including their commercial trade names, manufacturer, type, frequency range and force output, are given in Table I. The electric (Motomagnetic) exciter was operated from a 120 volt, 60 cps. power supply and the dynamic force output could be varied from 0 to 20 lbf by varying the voltage. A calibration of force versus voltage for this exciter is shown in Figure 13. Force was measured with a high sensitivity force transducer, which was purchased from PCB Piezotronics Co. expressly for the measurement of small forces at dynamic frequencies up to 50 kHz. The PCB transducer has a built-in amplifier system and the signal output is 10.1 millivolts per pound force. The pneumatic type exciter (Vibrolator) operates on the principle of centrifugal force, created by a revolving steel ball, driven by a flow of air. Force output is dependent upon speed of revolution and can be controlled by the amount of air pressure applied. The MB electromagnetic system has a variable frequency capability of 2 Hz to 70 kHz, based on the frequency range of the oscillator. In the course of the investigation, however, it was determined that the effective frequency was limited to a maximum of about 10 kHz by the mass of the exciter moving coil. The fourth system consisted of a Branson Model J17V Power Supply with a Sonic Converter (piezoelectric) transducer coupled to a tuned exponential horn. This low amplitude, high force system is rated to give a mechanical output of up to 1700 in-lbs per second at the tip of the horn with a displacement amplitude of 0.002 inch.

The experimental procedures employed to introduce sound vibration into metal samples were as follows. A steel specimen containing an edge fatigue crack approximately 0.38 inch in length was clamped in a fixture at one end of the specimen, as shown schematically in Figure 14. A 5 MHz ultrasonic contact probe was placed on the clamped end of the specimen in a position parallel to the plane of the crack. The echo signal from the crack was gated, amplified and fed to one channel of a Tektronix Type 561A Dual Trace Oscilloscope. This signal was also observed on the cathode ray tube of the ultrasonic reflectoscope. With no load applied to the specimen, the echo signal remained stationary on the oscilloscope screen. From the information acquired in Phase I of the program, it was known that application of static stresses would cause a change in echo amplitude to occur; an increase in amplitude with tensile stress and a decrease with compressive stress. Thus, if the stress required could be provided by introducing low frequency dynamic excitation (instead of by application of static forces) then a similar change in echo amplitude would be expected.

In the initial experiments to induce stress in the region of a crack by low frequency excitation, the test conditions were chosen to yield optimum effects. These conditions included the use of a relatively small test specimen with a large crack, amplification of the echo signal response with high gain settings and considerable "reject" of the signal. Also the low frequency exciter was placed in contact with the specimen in a direction parallel to the crack (see Figure 14), and normal to the axis of the specimen, so that the force applied would be amplified by a bending moment. In the performance of these experiments several problems were encountered as described below:

a) Difficulty in providing good coupling between contact (normal beam) search units and test specimens during application of dynamic excitation.

b) The problem of detecting and measuring the change in echo amplitude, as a function of dynamic stress, for cyclic rates greater than about 20 cycles per second.

c) Difficulty in providing an efficient transfer of acoustic energy from exciter to specimen when contact coupling was employed.

The problem of coupling at the interface between search unit and specimen was caused primarily by elastic rebounding of the search unit during application of dynamic excitation. This effect was reduced by preloading the search unit with a force sufficient to inhibit rebounding. Significant preloads, however, resulted in a gradual squeezing of the couplant oil from the interface, thus causing a change in transmission coefficient with time. Under these conditions the system was relatively unstable and reproducible data could not be obtained. The problem of coupling was not completely resolved for contact (normal beam) search units during dynamic excitation. A technique was developed, however, which allowed data to be obtained in a qualitative manner. This method consisted of cementing a 5 MHz contact, angle beam (shear wave) search unit to the side of the specimen. The search unit was placed in a position to give the optimum reflected signal from the crack with no stress applied to the specimen. Bonding of search unit to specimen was accomplished with a thin layer of contact cement (elastomeric type) which was allowed to cure for 24 hours with a small (approximately 2 lbs) preload. The use of a shear probe and this method of coupling resulted in a reduction in intensity of reflected signal. This system, however, was judged to be adequately stable for the intended purpose.

Early in the studies, it was realized that changes in echo amplitude, caused by dynamic excitation at cyclic rates higher than about 20 Hz, would occur more rapidly than could be observed with the unaided eye. To resolve this problem, the repetition rate of the ultrasonic input pulse was synchronized with the cyclic rate of the exciter to give a "stroboscopic" effect. In practice, these rates were adjusted slightly "off-synch" so that the echo signal amplitude was observed to change slowly. This method proved to be satisfactory for cyclic rates up to about 800 Hz (the maximum repetition rate of the ultrasonic instrumentation). In an attempt to extend the range of synchronization to rates higher than 800 Hz, a system was devised which consisted of a pulse generator with an electronic switch arrangement to modulate the cyclic rate of the exciter. Although this system did function adequately it was judged that a more desirable solution would be an extension in range of the ultrasonic input pulse rate.

In discussions with the manufacturer of the ultrasonic equipment (Automation Industries), it was learned that modifications could be made in the pulse generator circuit of the reflectoscope which would extend the maximum pulse repetition rate from 800 to 5000 Hz. Subsequent to these discussions, the modifications were made to the instrument and the unit was calibrated with an oscilloscope. The calibration curve of input pulse repetition rate as a function of pulse rate dial setting is given in Figure 15. It was determined that effective synchronization could be accomplished in the range of exciter frequencies from 80 to 2000 Hz. It was also determined that synchronization could be extended to frequencies as high as 5000 Hz, under limited conditions, but with significant loss in signal amplitude. For exciter frequencies in the range from 5000 Hz to 20,000 Hz, synchronization was accomplished by adjusting the input pulse rate in proportion to the exciter frequency. As an example, for an exciter frequency of 10,000 Hz the pulse rate was adjusted to 5000 Hz and synchronization occurred on alternate cycles. In practice, however, synchronizing at frequencies above 5000 Hz was found to be considerably more difficult to accomplish than synchronizing at frequencies below 5000 Hz.

One of the most formidable problems encountered in the Phase II studies was the difficulty in providing an efficient transfer of energy from the low frequency exciters to the test specimen. In the performance of the experimentation, both solid coupling and contact coupling techniques were employed in conjunction with a number of different methods of supporting the specimen during the tests. The most effective procedures were found to be the solid coupling of exciters to specimen, and the operation of the exciters in the range of cyclic frequencies from 100 to 1000 Hz, approximately. These procedures, in effect, are low force fatigue tests and they appear to have no distinct advantage over static loading in providing tensile stress in the region of a crack. Attempts to induce stress in the test specimens with exciters operating at frequencies above 1000 Hz proved to be mostly unsuccessful, although some small stress effects were observed under limited conditions. A summary of the significant results obtained from the tests in Phase II are presented in Table II. Included in this Table are the operating frequency of the various exciters, the type of coupling used in the test, the force output measured dynamically at the operating frequency, the stress produced at the crack location (bending mode and also axial tension mode) and the corresponding increase in echo amplitude. Measurements of echo amplitude changes were accomplished dynamically by synchronizing the input pulse repetition rate of the reflectoscope with the operating frequency of the exciter. As noted previously, synchronization at exciter frequencies greater than about 2000 Hz proved to be quite difficult.

One of the main objectives of the Phase II studies was to investigate the feasibility of inducing significant stresses in a steel specimen with excitation frequencies above the audible range (e.g. 20 kHz). It was also hoped that this could be accomplished with moderate power requirements. In accordance with this objective, several experiments were performed using the Branson (peizoelectric) transducer operating at a resonant frequency of 20 kHz with 75 watts (average) output power. When used in conjunction with a titanium exponential horn, tuned to resonate at 20 kHz, a force output exceeding 40 pounds and a displacement amplitude of 0.002 inch was achieved at the tip of the horn under no load conditions. It was expected that the force-amplitude ratio at the horn tip would be sufficient to induce significant stresses in the crack region when the horn was placed in contact with the test specimen.

Under the optimized conditions employed for these tests, the magnitude of tensile stress acting on the crack need only be of the order of magnitude of 100 psi to cause a change in echo amplitude of 5 divisions on the reflectoscope screen. In the performance of the tests, however, the expected echo amplitude changes were not observed, indicating that either the stress induced was very small or synchronization with pulse repetition rate was not accomplished. Further investigations revealed that part of the problem was caused by poor contact coupling of horn tip to specimen surface. Improved coupling was obtained by preloading the Branson transducer. However, preloads sufficient for improvement in coupling also caused the horn to detune, due to excessive damping, when the horn was contacted tightly to the highly resistive load (test specimen).

The problem of excessive damping may be partially relieved by reducing the fraction of the cycle that the load is in contact with the horn, or by limiting the number of cycles that the horn is in contact with the load. A procedure was devised, therefore, to drive the Branson with the MB exciter. With this procedure, the Branson horn tip was contacted with the specimen at the cyclic rate of the MB, thereby limiting the number of cycles of contact with the specimen. The MB exciter was operated in a range of frequencies from 100 to 1000 Hz, and tests were performed both with the Branson activated (at 20 kHz) and with the Branson turned off. Synchronization in each instance was accomplished at the MB frequencies. The results obtained from these experiments are shown in Figure 16 with the total observed change in echo amplitude given as a function of MB exciter frequency. These data show that a small improvement in response occurred at a driving frequency of 100 Hz, and a more significant improvement occurred at about 650 Hz. It should be noted, however, that the echo amplitude response observed here was obtained from tests performed in a bending mode. When the excitation was introduced into the specimen in an axial mode (normal to the plane of the crack), the response was negligible.

IV. DISCUSSION OF RESULTS

The results obtained in Phase I of the program have demonstrated that the amount of ultrasonic energy reflected from a thin crack in steel is very sensitive to changes in stress intensity at the crack tips. Reflected energy is increased by tensile stress and decreased by compressive stress acting on the crack, and the effect is maximum when the stress is acting in a direction normal to the crack plane. Thus, in effect, a crack in compression is more difficult to detect than an unstressed crack. On the other hand, the detection of thin cracks is enhanced by applying tensile stress to increase the stress intensity at the crack tips, provided that care is taken to be sure that the stress intensity does not exceed the critical value required for crack extension.

It is proposed that these effects can be explained, in part, by postulating that thin cracks are analogous to thin films in solids. In this case, the relationship derived by Rayleigh (Equation 1) predicts that a change in intensity of reflected waves will occur with a change in crack opening, if the original crack opening is within a critical range of values. The relationship between crack opening and the intensity of reflected waves is dependent upon the acoustic impedance mismatch between the respective media involved, and also on the wavelength of sound in the media contained within the crack boundaries. It is predicted that full reflection is not possible; however, very close to full reflection is obtained for large impedance mismatch and crack openings exceeding the critical range.

The analogy to thin films is useful in that a change in intensity of reflected waves is predicted to be related to a change in crack opening, or crack opening displacement (COD). The relationship between COD and applied stress (or stress intensity at the crack tip) can be obtained for specific crack geometries, using linear elastic fracture mechanics analyses. Thus, in principle, the change in reflection coefficient can be expressed in terms of stress intensity changes at the crack tips.

The effect of stress on ultrasonic energy reflected from thin cracks can be determined experimentally, and considerable data was obtained in the program to illustrate this effect. It is important to note, however, that the usefulness of the data is dependent upon an understanding of all factors pertinent to this relationship. Qualitatively it has been shown that these factors include the characteristics of the ultrasonic instrumentation, the characteristics of the test material and the crack geometry. As with most techniques used in NDT practice, the response of the instrumentation employed must be established by calibration against suitable standards for the test materials of interest.

The results of studies in Phase II, to explore the feasibility of inducing stress in metal samples with low frequency excitation in the range of 10 to 20 kHz, were not encouraging. Based on the data obtained in this phase of the program under optimized conditions, it appears that effective use of low frequency exciters to induce stress is limited to the cyclic frequency range of 1000 Hz and below. In general, the test results indicated that the stress induced in this range was proportional to the effective force transferred to the test specimen from the exciter. Transfer was best accomplished with solid coupling of exciter to specimen. A greater effect was observed with less force when the frequency of the exciter was tuned to the natural frequency of the system.

Attempts to provide significant stress in metal samples with excitation at higher frequencies (e.g. 20 kHz) were unsuccessful. Considerable difficulties were encountered in detecting changes in echo amplitude at this frequency, and the efficiency of transfer of acoustic energy from transducer horn to specimen was quite low. Some improvement was obtained by driving the 20 kHz transducer with a lower frequency exciter, thereby reducing the problem of excessive damping. The net effect, however, was considerably less than was observed at lower frequencies with solid coupling.

V. CONCLUSIONS

On the basis of the analyses, experimental results and discussion presented herein, the following is concluded:

1. The intensity of ultrasonic echo signals reflected from thin flat cracks in solids is decreased by compressive stress and increased by tensile stress acting normal to the plane of the crack. Thus a crack in compression is more difficult to detect with ultrasonic pulse-echo than an unstressed crack, and the capability of detecting the crack is improved by application of tensile stress.

2. The change in intensity of echo signals with applied stress is related to the change in effective crack opening, which in turn is a function of the stress intensity at the crack tip. For this response to occur, the initial crack opening must be within a critical range of values. The critical range is a function of acoustic impedance mismatch at the crack interface, and also the frequency of the ultrasonic input pulse. The response was observed for all cracks studied in this investigation; including fatigue cracks in aluminum and steel, and cracks induced in glass plates.

3. The effect of stress on echo response was observed for stresses applied either statically or dynamically in an axial mode and also in a bending mode. The response was measured successfully with both ultrasonic longitudinal wave and with shear wave search units.

4. The use of low frequency excitation to induce stress in metal samples appears to be limited to the cyclic frequency range of 1000 Hz and below. Best results were obtained with solid coupling of exciter to test material.

5. Attempts to induce stress with excitation at 20 kHz were not successful with the techniques and equipment used in these studies. Although a small effect was observed, it was judged that this method does not appear to be feasible for providing improvement in crack detection in NDT practice. It is recognized that the potential of this method could probably be increased with the use of transducers at much higher levels of power (e.g. sonic motors), capable of mechanical energy transfer at levels of 15 or more horsepower. At present, however, it does not appear worthwhile to pursue this possibility, since it has been demonstrated that the desired stresses are more easily introduced by static loading.

VI. PRACTICAL APPLICATIONS

The primary objective of the research program was to study the effect of stress fields on the ultrasonic energy reflected from thin flat cracks for the purpose of utilizing this effect for improvement in crack detection. It is the opinion of the authors that the information obtained in this program will be beneficial in this respect.

As an example of possible application to NDT practice, it is suggested that consideration be given to ultrasonic pulse-echo inspection of components, vehicles or structures during application of design stress to the system. An illustration of this type of procedure would be the inspection of pressure vessels while the vessel is being proof tested. With this method of pulse-echo inspection at proof loads, several benefits may be gained:

1) Cracks oriented in a direction normal to applied tensile stress may be more easily detected. From a potential failure standpoint, cracks located thusly can be most critical for Mode I (crack opening mode) fracture, depending on the size of the crack and the fracture toughness of the material. Cracks oriented parallel to tensile stress should effect little or no change in echo response. These cracks, fortunately, are of a lesser concern as long as the direction of principal stress remains unchanged. In effect, this means that inspection of systems with pulse-echo, during loading to the design stress, can provide improvement in the detection of those cracks most critically located.

2) By observing echo signals from a detected crack during rising load, it may be determined whether the crack is being acted on by tensile stress (increasing echo amplitude) or compressive stress (decreasing echo amplitude) in the particular service application.

Another possible practical application of results obtained in this research program is the use of the "synchronizing" technique, described in Phase II, for looking (ultrasonically speaking) at cracks subjected to dynamic stress (e.g. fatigue) in service. This technique can be used either in searching for undetected cracks in dynamic systems, or for observing changes in the behavior of cracks already detected.

Future plans are to study the ultrasonic echo response from other types of discontinuities in solids, in addition to the response from thin flat cracks. It should be possible to relate changes in echo amplitude and pattern, as a function of applied stress, to specific distinguishing features of a given type of flaw.

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2. A.E. Green and I.N. Sneddon, "The Distribution of Stress in the Neighborhood of a Flat Elliptical Crack in an Elastic Solid," Proceedings, Cambridge Phil. Soc., Vol. 46, (1950).

3. J.G. Sessler and V. Weiss, "Improvement in Flaw Detection by the Ultrasonic Pulse-Echo Technique with Simultaneous Low Frequency Excitation", Final Report, ARPA Contract N00140-69-C-0121, Syracuse University Research Corporation, (Nov. 1969).

4. ASTM Designation: E127-64, "Recommended Practice for Fabricating and Checking Aluminum Alloy Ultrasonic Reference Blocks," ASTM Standards, Part 31, (May 1969).

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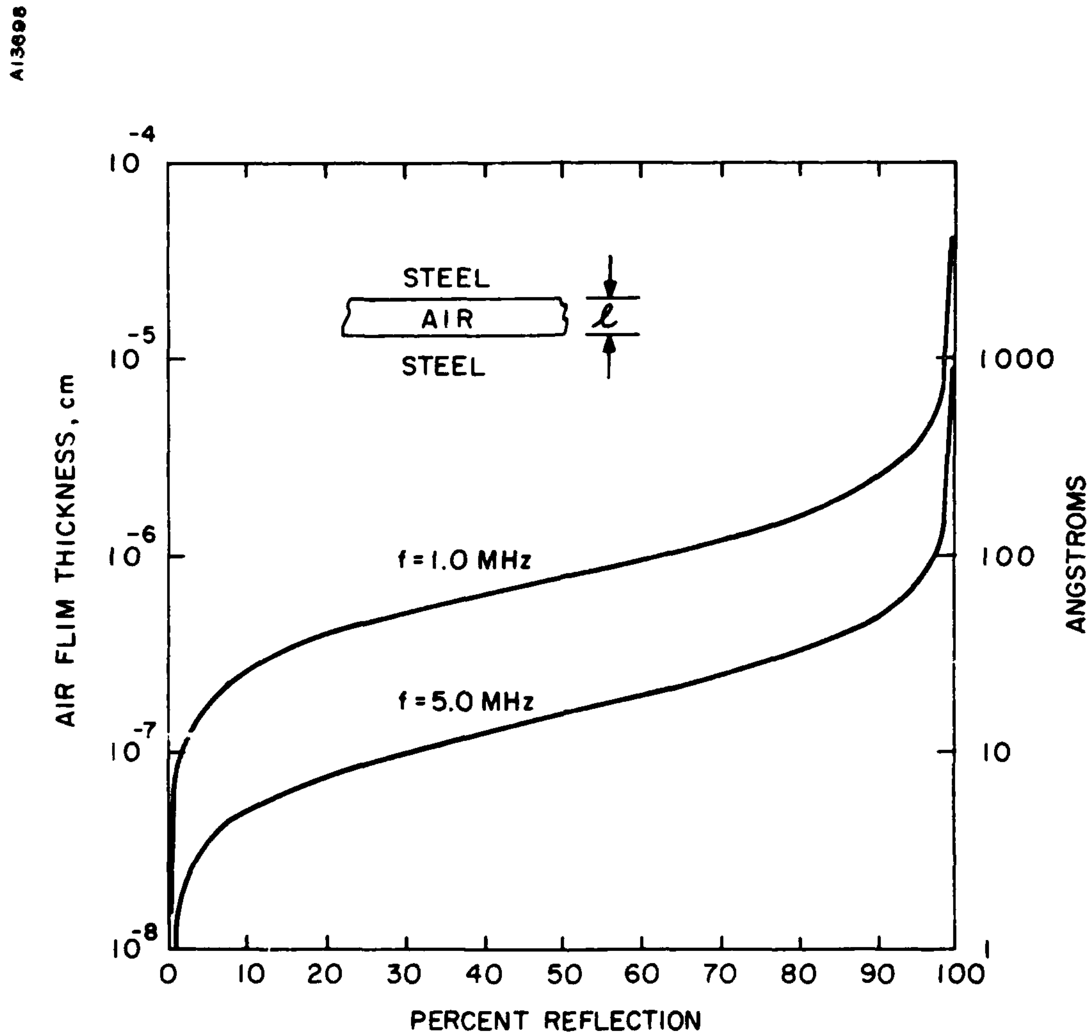

FIGURE 1. PERCENT REFLECTION AS A FUNCTION OF AIR FILM THICKNESS ACCORDING TO EQUATION 1.

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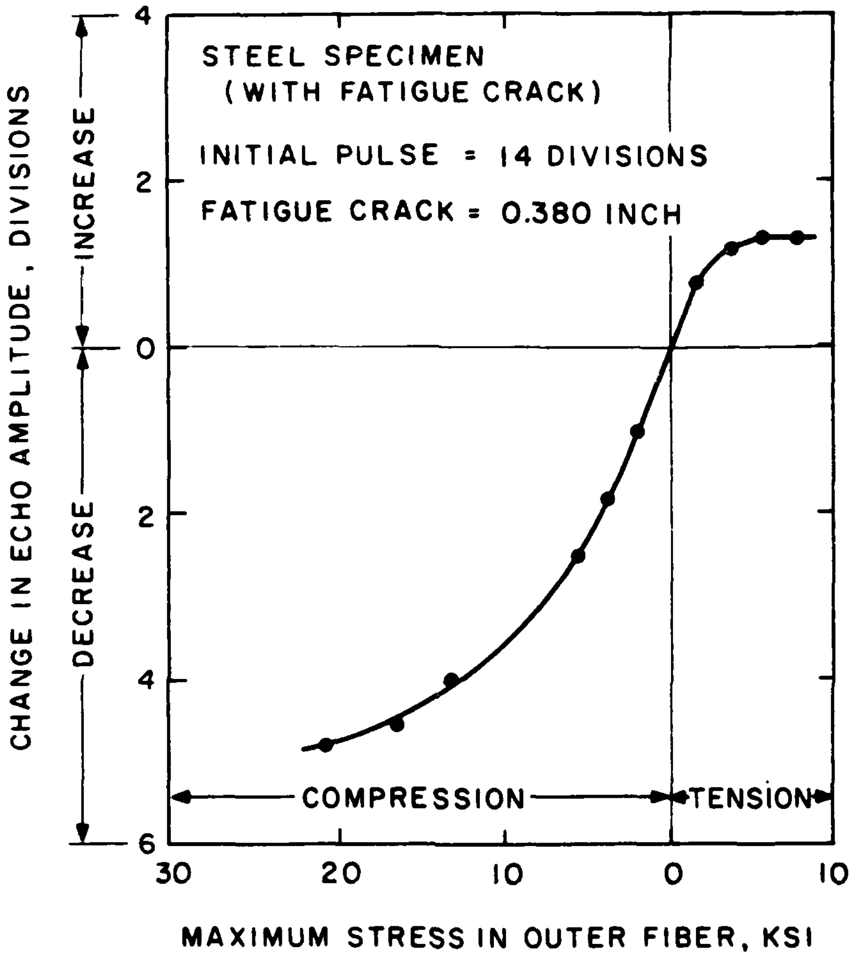

FIGURE 2. EFFECT OF STRESS ON AMPLITUDE OF SIGNAL REFLECTED FROM FATIGUE CRACK IN STEEL SPECIMEN.

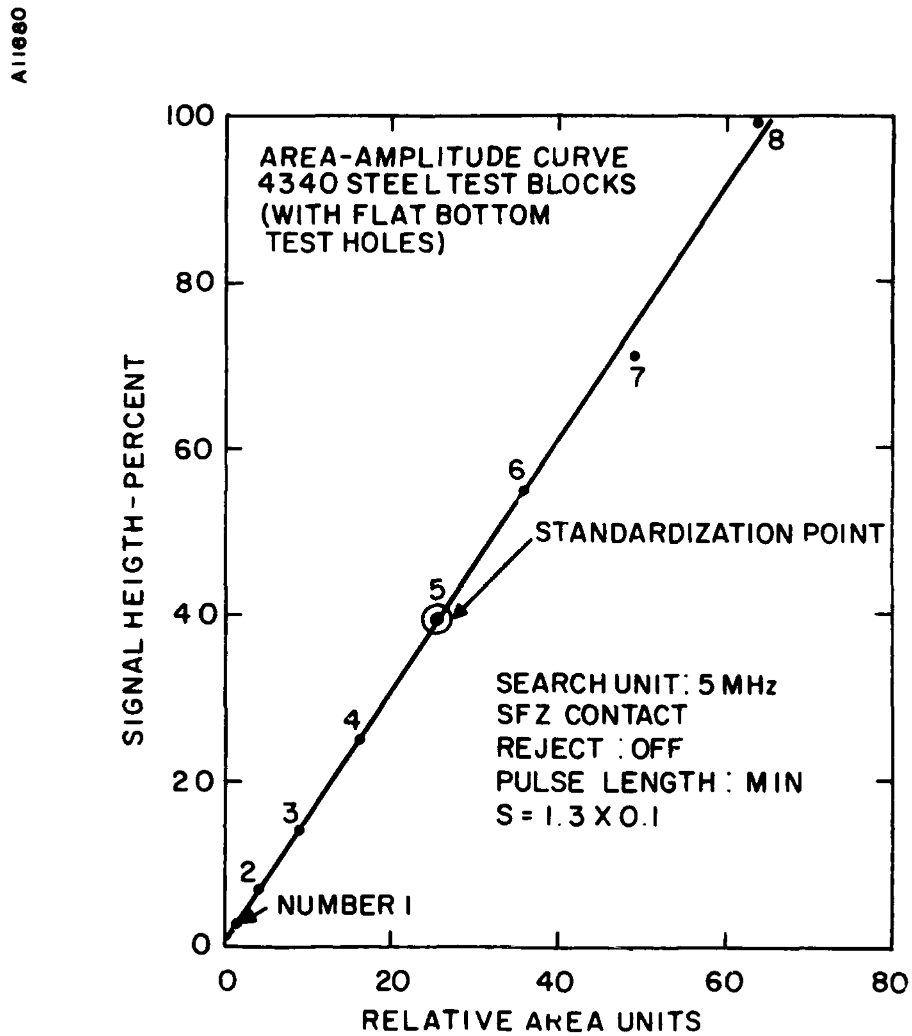

FIGURE 3. AREA-AMPLITUDE RESPONSE CURVE OBTAINED WITH 4340 STEEL FLAT BOTTOM HOLE STANDARD REFERENCE BLOCKS. HOLE DIAMETERS ARE 1/64 INCH STEPS.

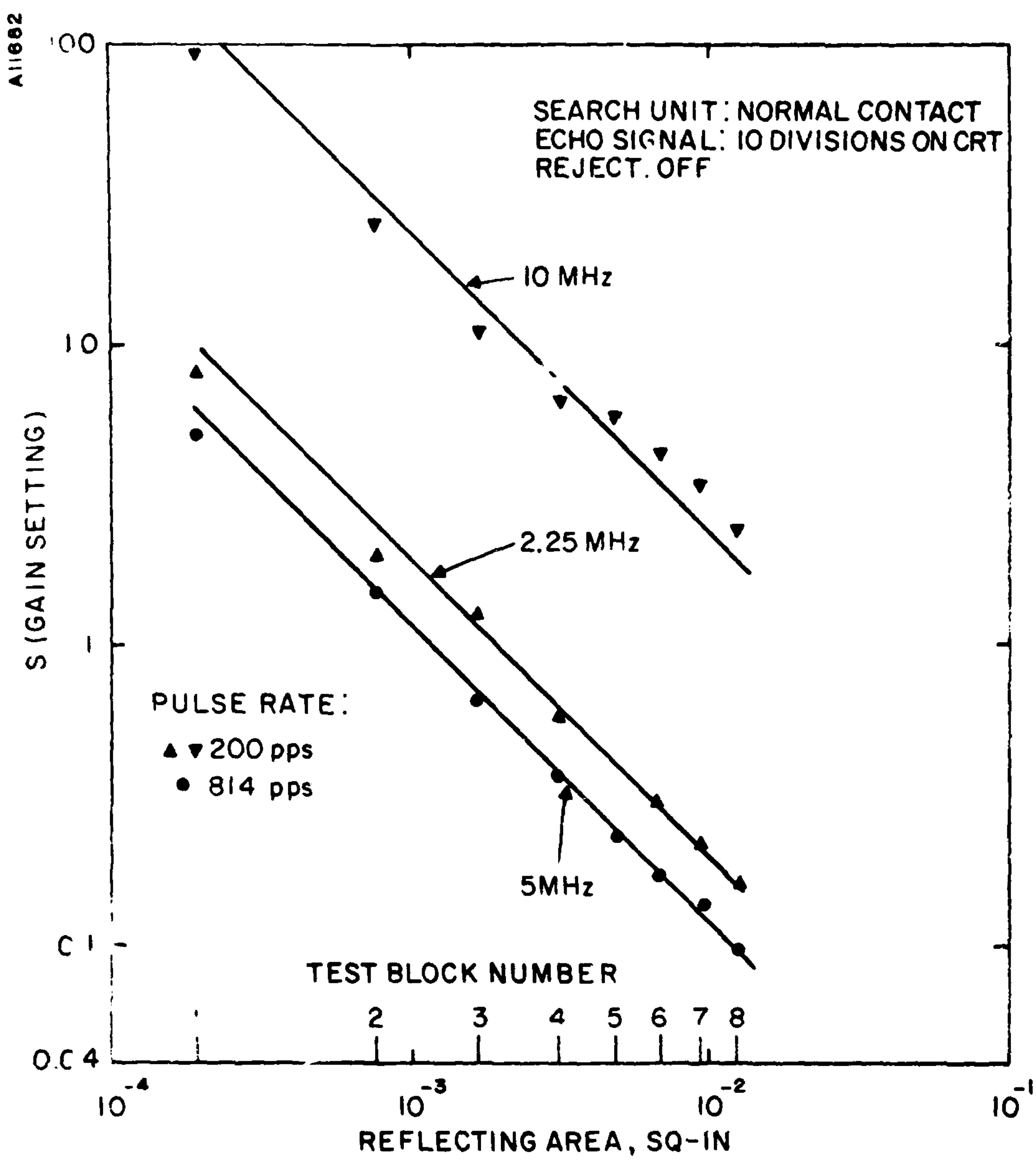

FIGURE 4. CALIBRATION OF ULTRASONIC PULSE-ECHO SYSTEM OBTAINED WITH 4340 STEEL TEST BLOCKS.

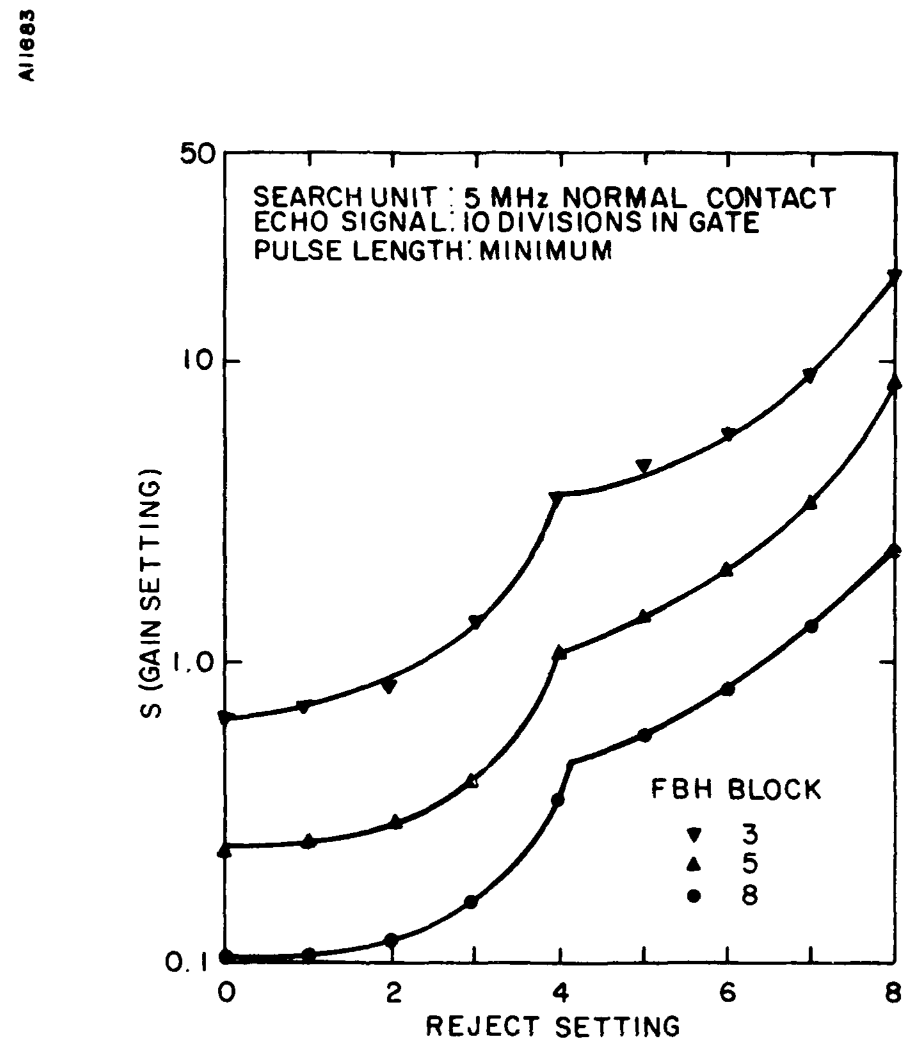

FIGURE 5. EFFECT OF REJECT CONTROLS AS DETERMINED WITH FLAT BOTTOM HOLE 4340 STEEL TEST BLOCKS.

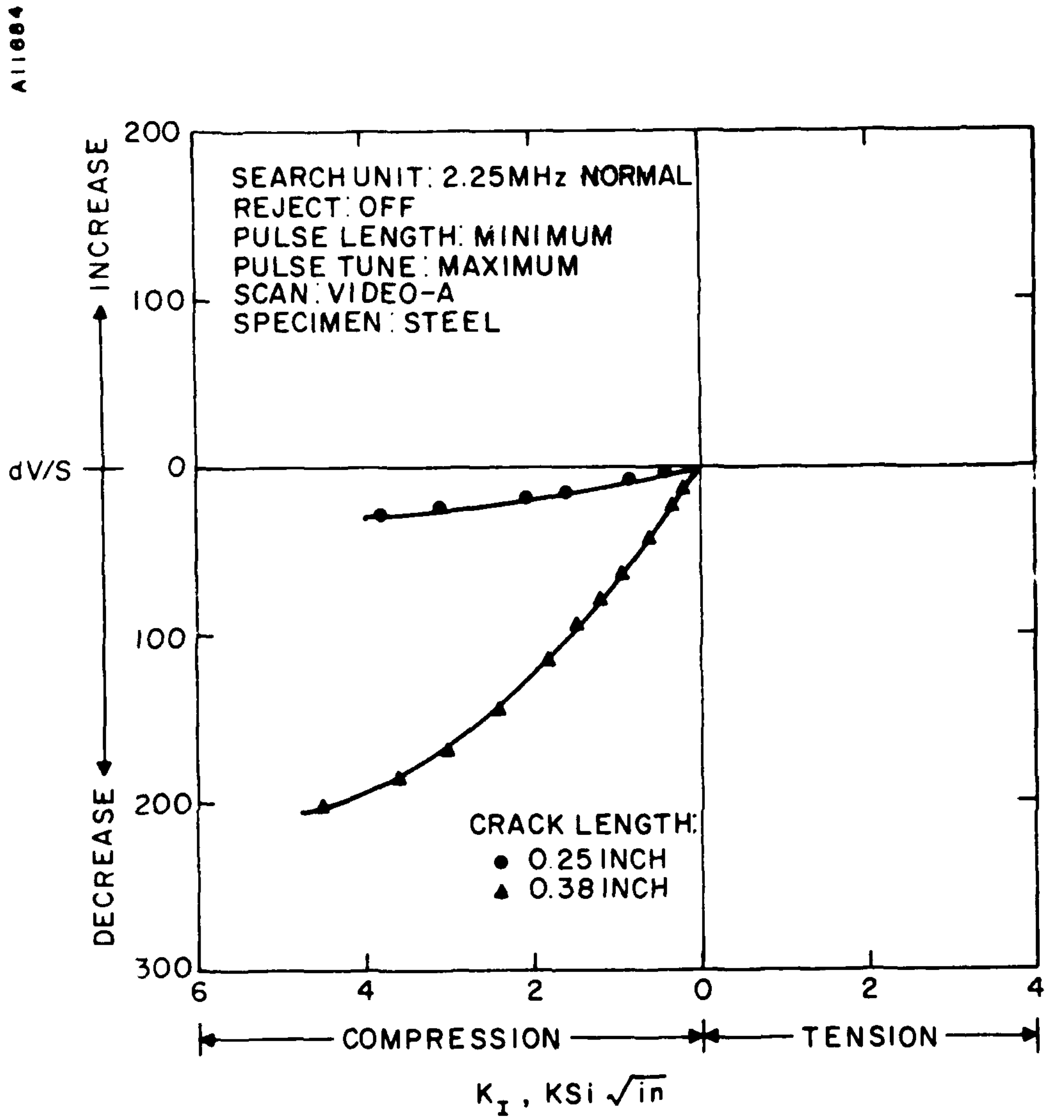

FIGURE 6. EFFECT OF STRESS INTENSITY AT CRACK TIP ON AMPLITUDE OF ECHO FROM CRACK INTERFACE DETERMINED WITH 2.25 MHz NORMAL CONTACT SEARCH UNIT.

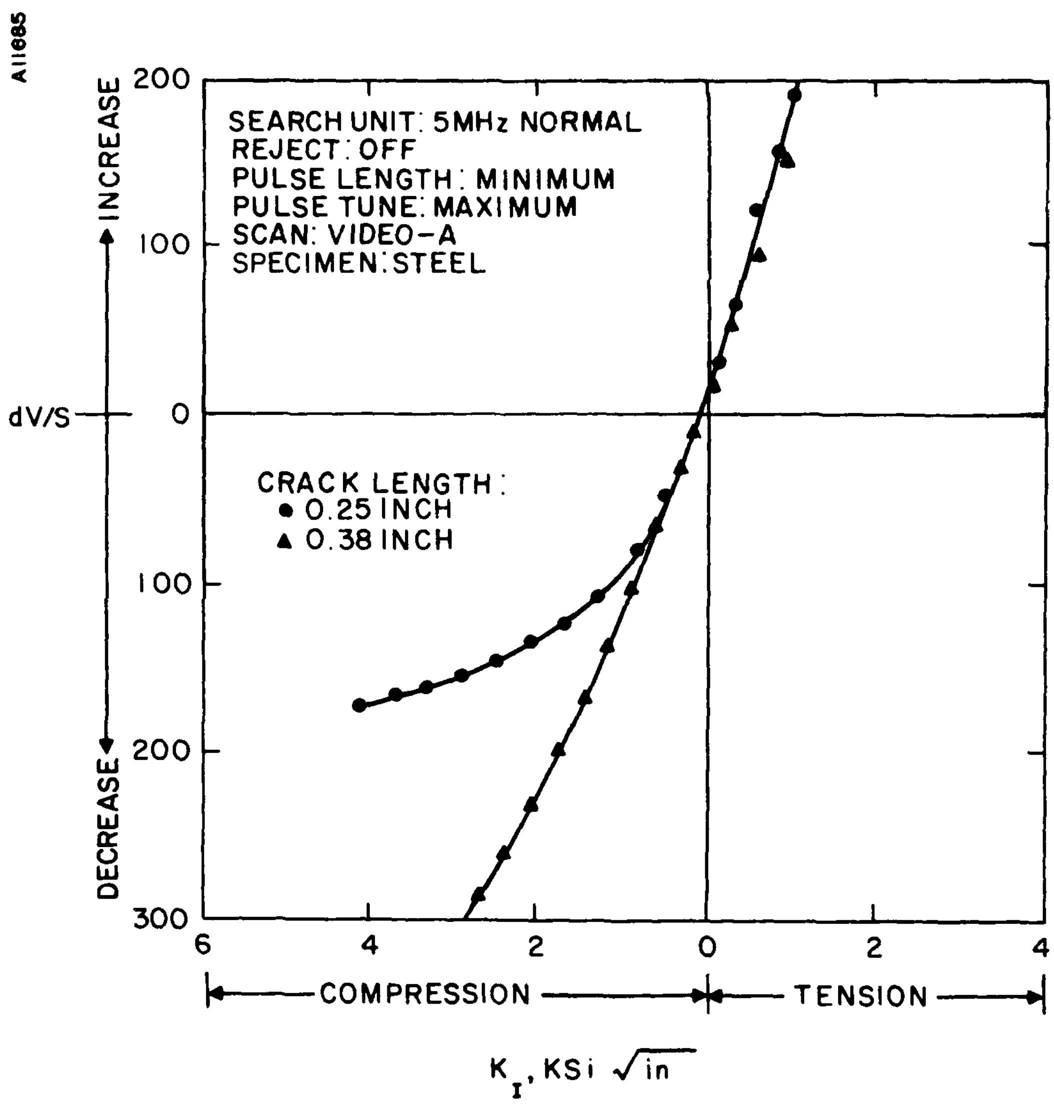

FIGURE 7. EFFECT OF STRESS INTENSITY AT CRACK TIP ON AMPLITUDE OF ECHO FROM CRACK INTERFACE DETERMINED WITH 5 MHz NORMAL CONTACT SEARCH UNIT.

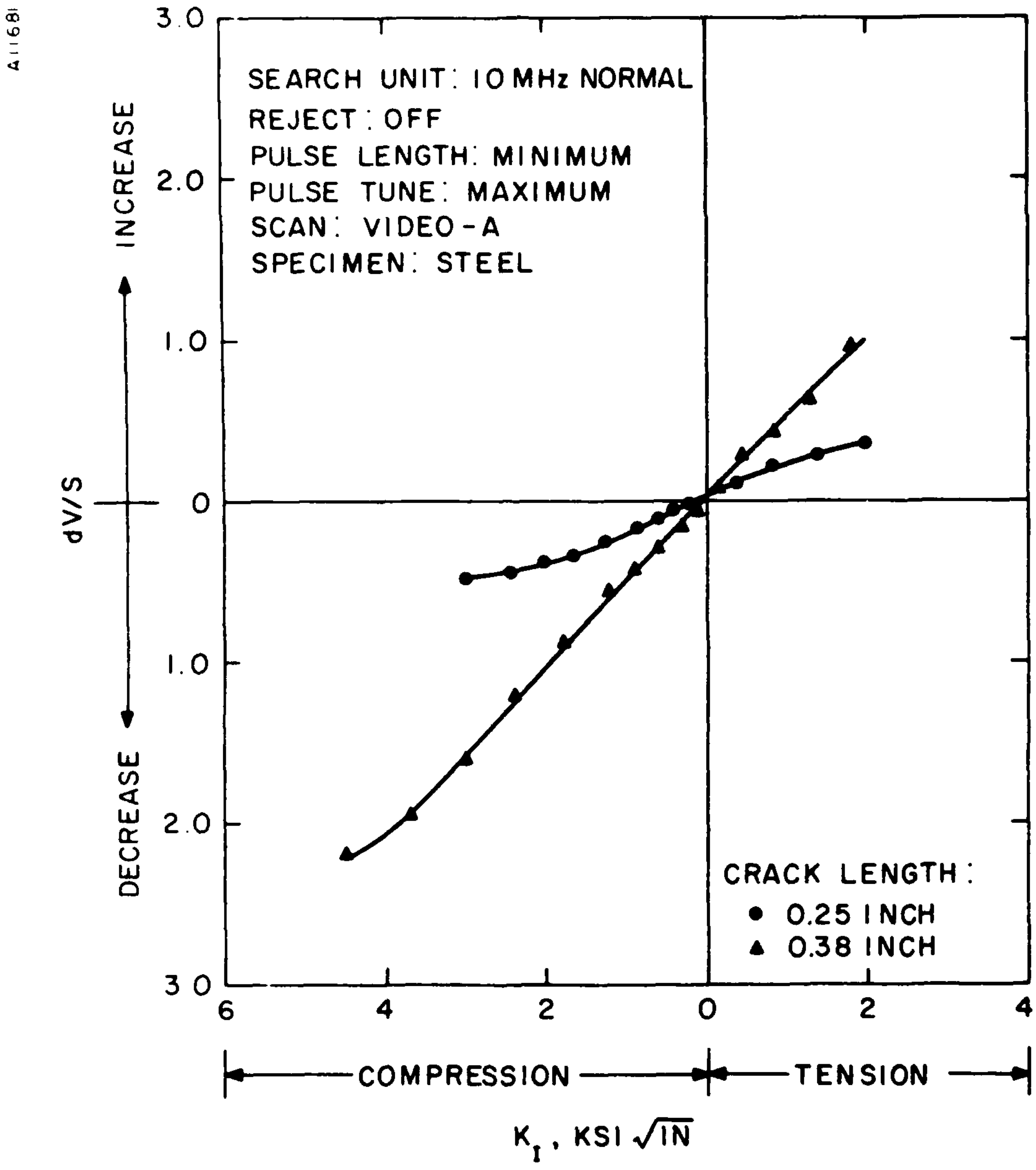

FIGURE 8. EFFECT OF STRESS INTENSITY AT CRACK TIP ON AMPLITUDE OF ECHO FROM CRACK INTERFACE DETERMINED WITH 10 MHz NORMAL CONTACT SEARCH UNIT.

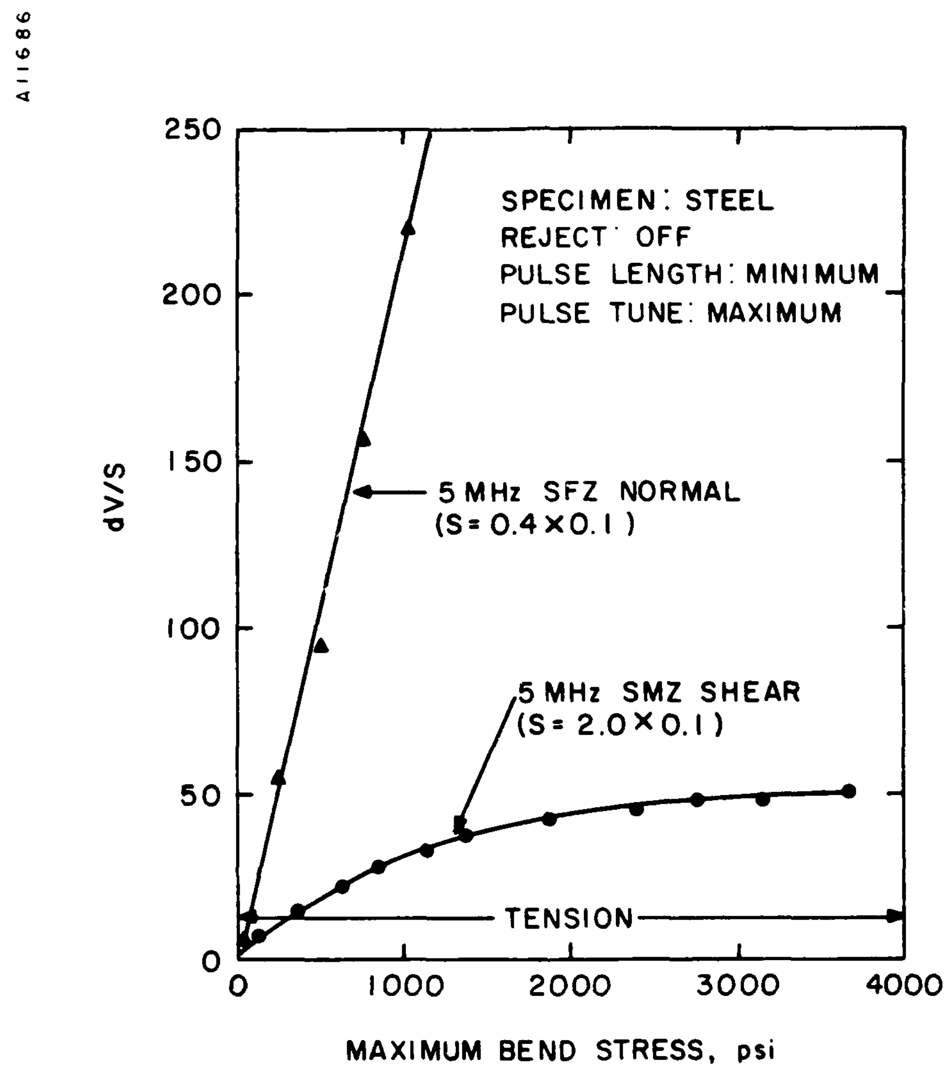

FIGURE 9. EFFECT OF STRESS ON ECHO AMPLITUDE AS MEASURED WITH CONTACT NORMAL BEAM AND SHEAR PROBE SEARCH UNITS.

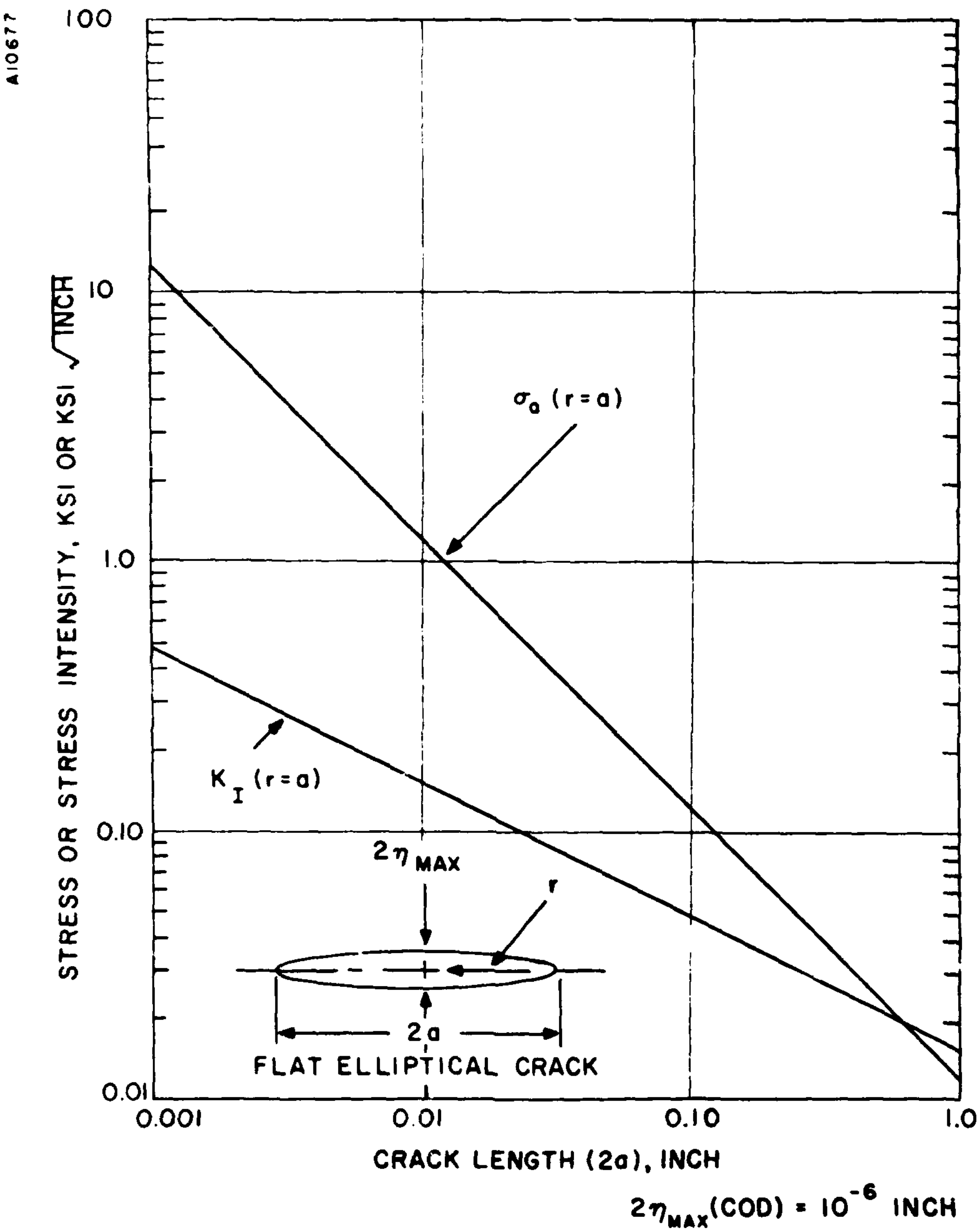

FIGURE 10. GROSS SECTION STRESS (σ_a) OR STRESS INTENSITY AT CRACK TIP (K_I) REQUIRED FOR CRACK OPENING DISPLACEMENT OF 10^{-6} INCH.

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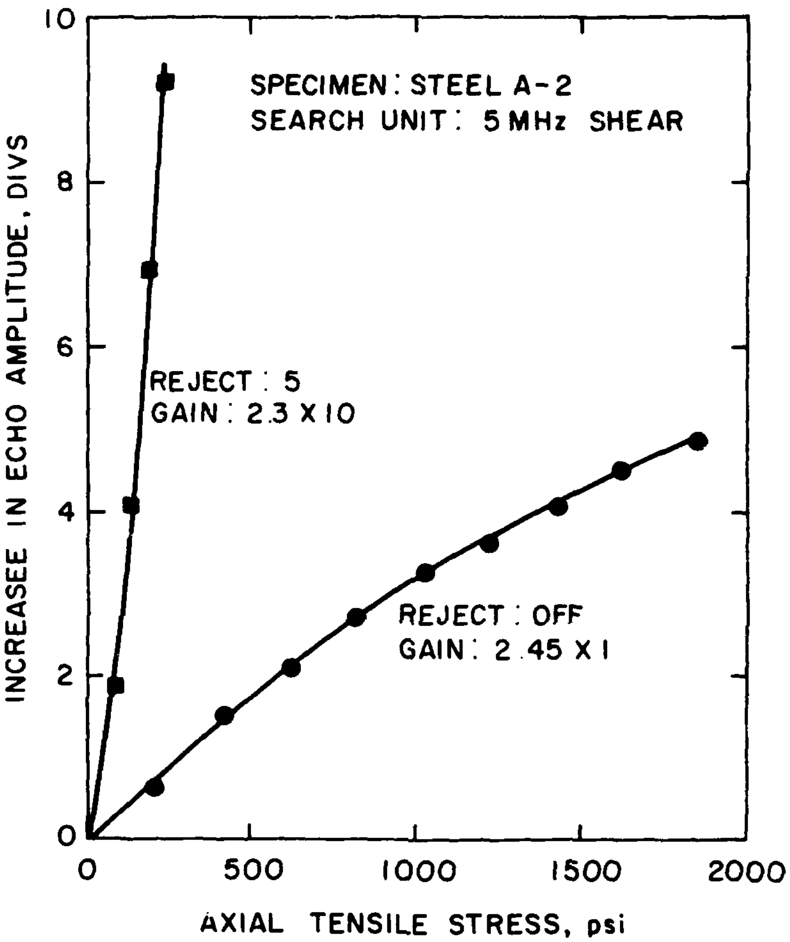

FIGURE 11. EFFECT OF AXIAL TENSILE STRESS ON ECHO AMPLITUDE FOR TWO CONDITIONS OF SIGNAL REJECT.

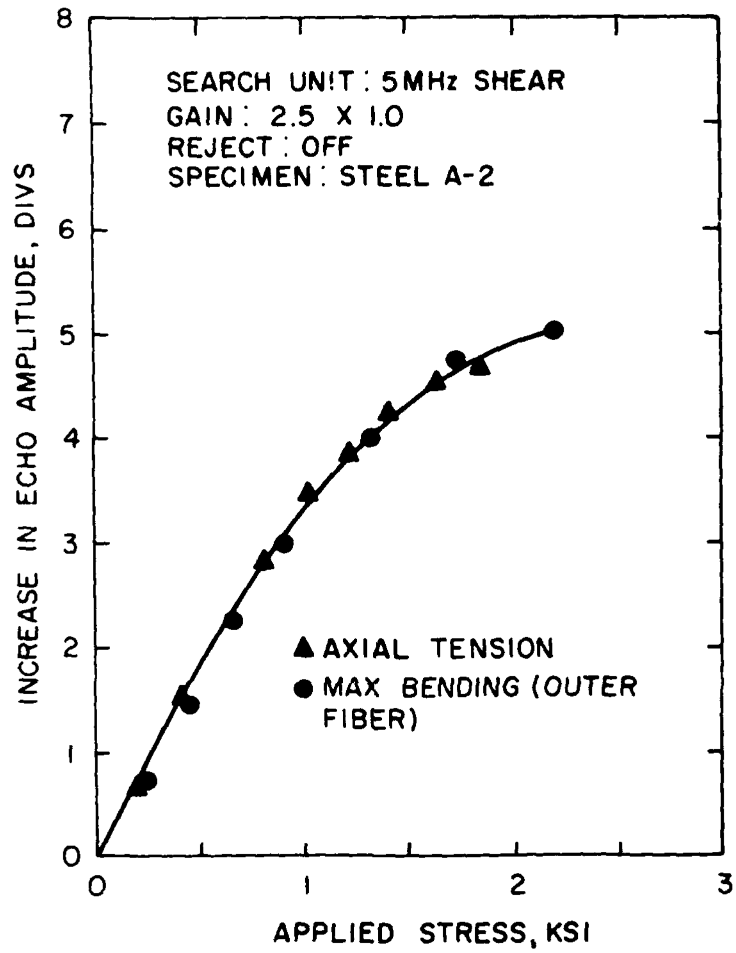

FIGURE 12. COMPARISON OF THE EFFECT OF BEND STRESS AND AXIAL TENSION STRESS ON ECHO AMPLITUDE.

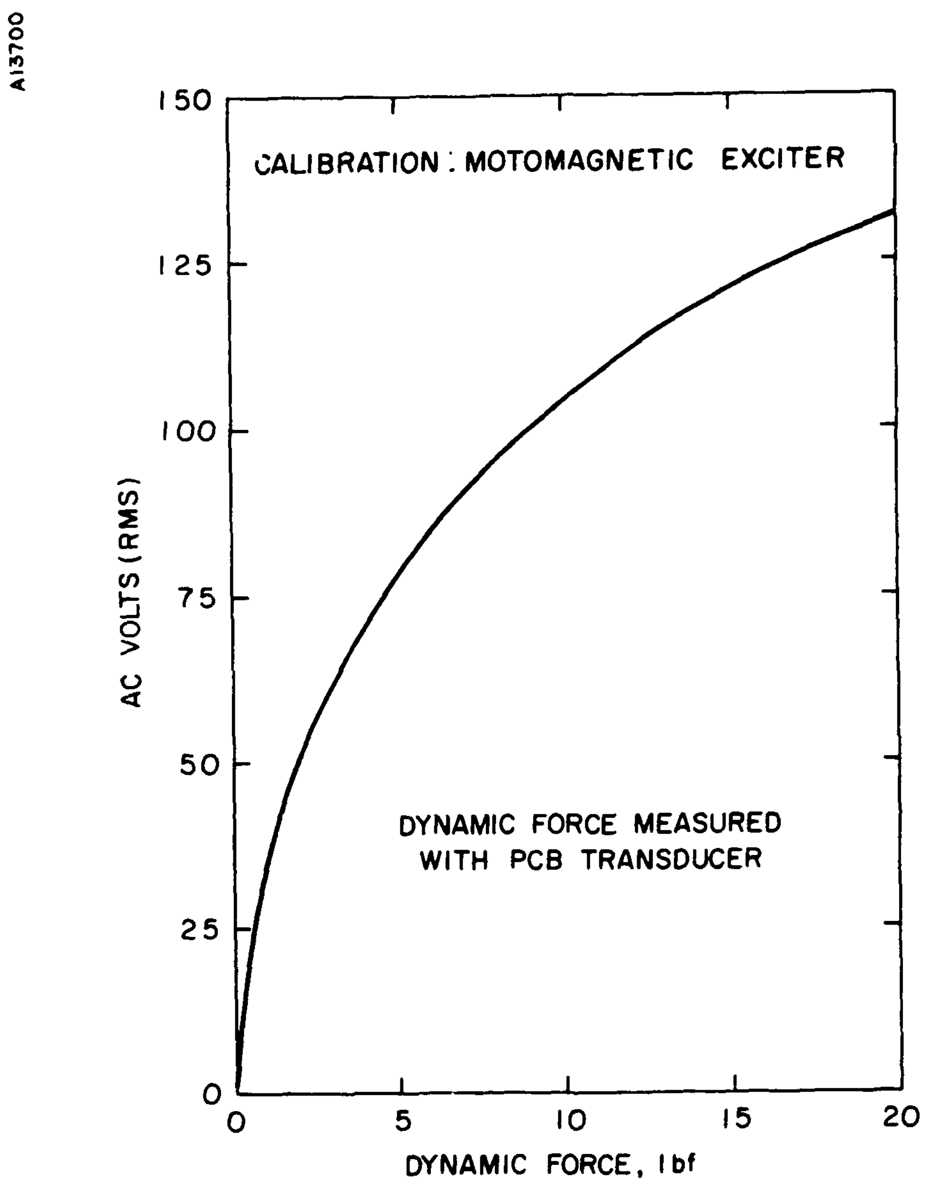

FIGURE 13. CALIBRATION OF DYNAMIC FORCE OUTPUT VERSUS APPLIED VOLTAGE FOR MOTOMAGNETIC EXCITER.

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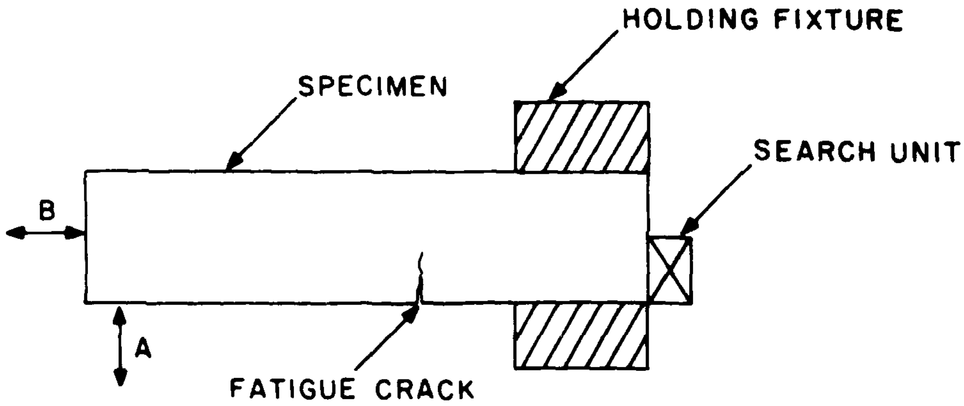

A BRANSON TRANSDUCER WITH EXPONENTIAL HORN (20 kHz) APPLIED PARALLEL TO CRACK.

B BRANSON TRANSDUCER WITH EXPONENTIAL HORN (20 kHz) APPLIED NORMAL TO CRACK.

FIGURE 14. SCHEMATIC DIAGRAM OF TEST CONFIGURATION FOR APPLYING LOW FREQUENCY EXCITATION TO TEST SPECIMEN.

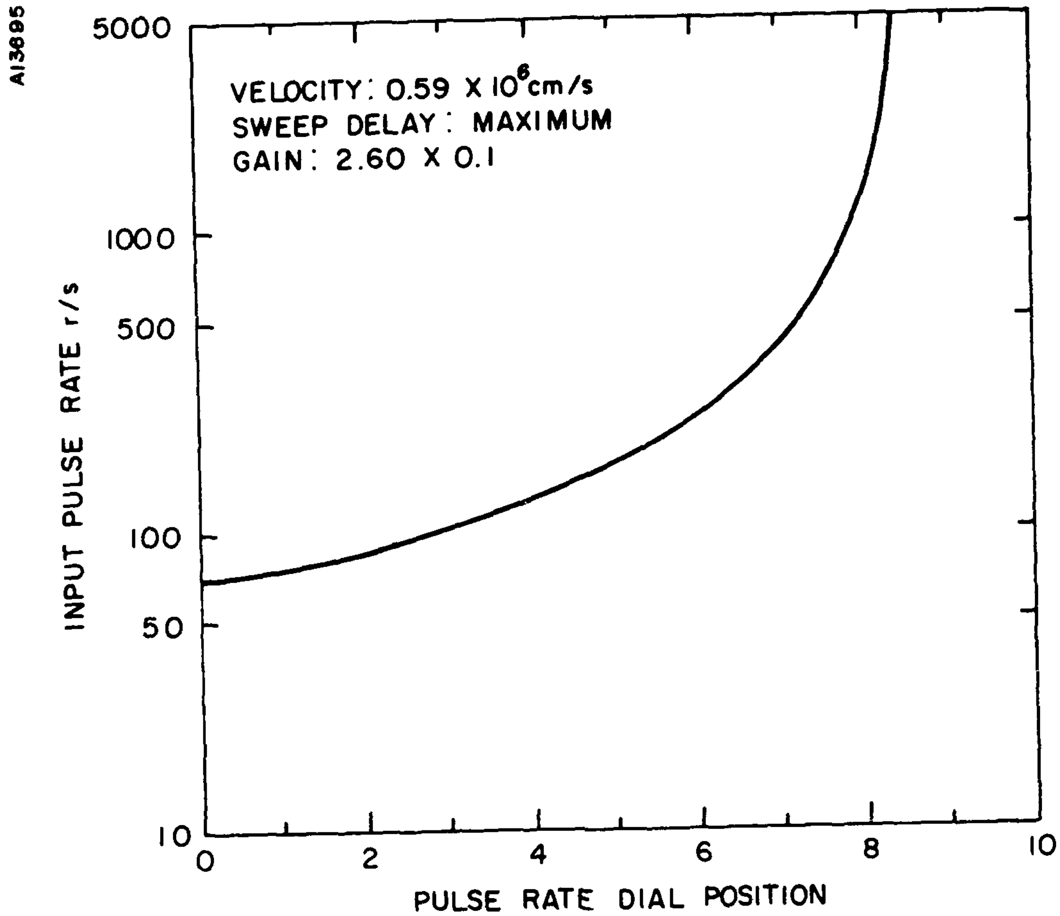

FIGURE 15. CALIBRATION OF INPUT PULSE REPETITION RATE AS A FUNCTION OF DIAL POSITION.

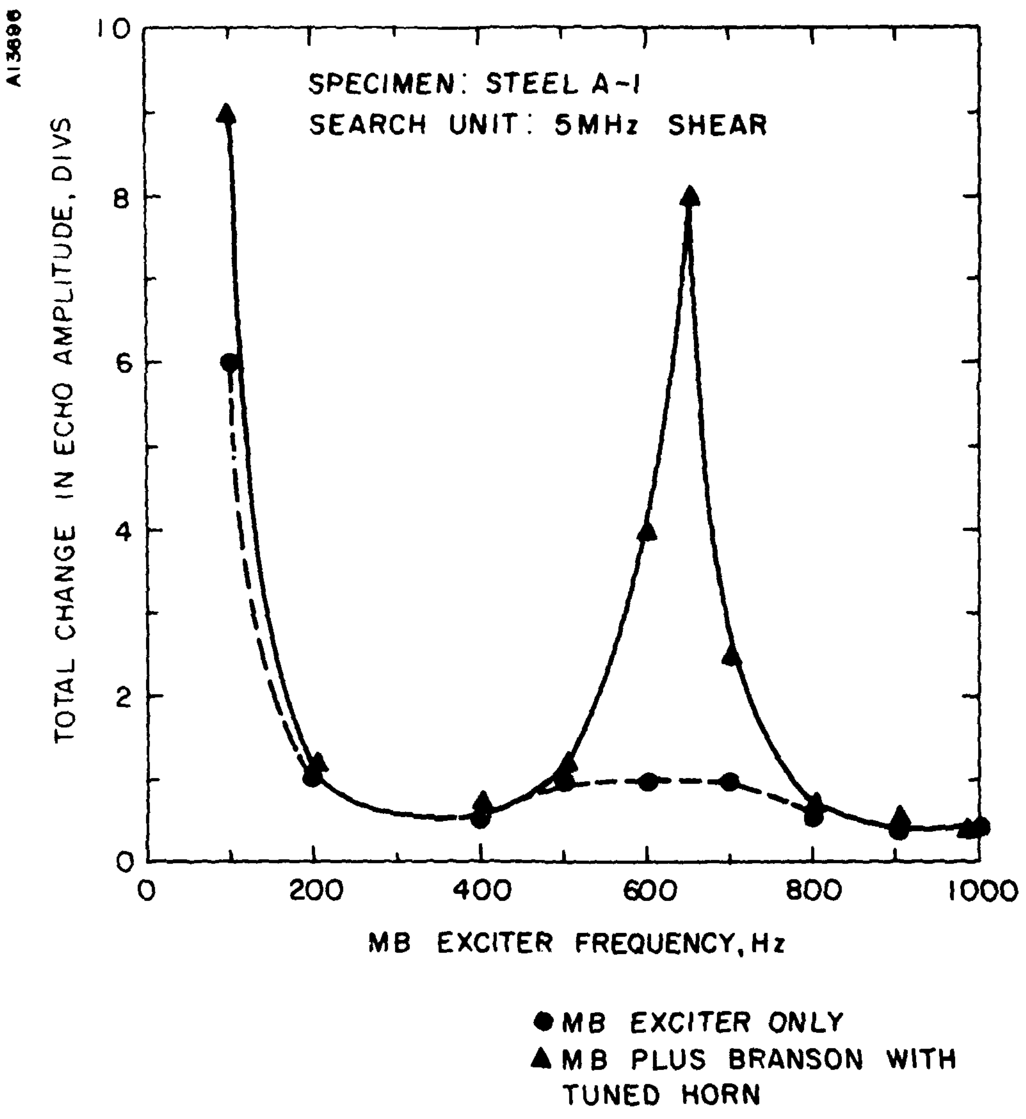

FIGURE 16. CHANGE IN ECHO AMPLITUDE OBSERVED FOR MB EXCITER AND MB COMBINED WITH BRANSON FOR MB FREQUENCIES IN THE RANGE FROM 100 TO 1000 Hz.

Table I

Characteristics of the Exciters Used for the Investigation

Trade Name	Manufacturer	Type	Frequency Range (Hz)	Max Output Force (lbf)
Motomagnetic (Model AVE 20)	Martin Eng. Co.	Electric	120	20
Vibrolator (Model CV-10)	Martin Eng. Co.	Air Driven Rotating ball	10 to 450	50
MB Vibration Exciter (Model SC)	MB Mfg. Co.	Electromagnetic	20 to 10,000	10
Branson Sonic Converter with Exponential Tuned Horn (Model J17V)	Branson	Piezoelectric (Lead Zirconate titanate crystal)	20,000	(a)

(a) Produces up to 1700 in-lbf energy per second at tip of horn (equivalent to 190 watts, approx.)

Table II

Effect of Low Frequency Excitation on Echo Amplitude for Several Types of Exciters

Exciter	Type	Frequency (Hz)	Type of Coupling Used	Force Output (a) (lbf)	Stress at Crack Location (psi)		Increase in Echo Signal ΔU (divs)	
					σ_B	σ_T	Bend	Axial
[illegible]magnetic Model [illegible]	Electric	120	Solid	20	575	28	15	0.8
Vibrolator (Model [illegible])	Air driven rotating ball	420	Solid	50	1,440	70	38	2
		350	Solid	36	1,040	50	27	1.4
		280	Solid	25	720	35	18	1
MB	Electro-Magnetic	100	Solid	28	810	40	21	1.2
		500	Solid	26	750	37	19	1.0
		1,000	Solid	12	350	18	9	< 1.0
		2,000	Solid	7	200	10	5.2	(c)
		5,000	Solid	5	144	7	3.8	(c)
		10,000	Solid	3.7	108	5	2.8	(c)
		100	Contact	8(b)	220	11	6	(c)
		200-500	Contact	1.5(b)	40	2	1.0	(c)
		800	Contact	< 1.0(b)	(c)	(c)	< 1.0	(c)
Branson	Piezo-electric	20,000	Contact	42	(c)	(c)	< 1.0	(c)
MB plus Branson	Piezo (20 kHz) driven by MB	100	Contact	12	350	18	9	< 1.0
		650	Contact	11	310	15	8	< 1.0
		1,000	Contact	1	30	1.5	0.5	(c)

Specimen: Steel A-1 (with 0.38 inch crack)
Sensitivity: 4.0 x 1.0
Reject Setting: 5
Search Unit: 5 mHz Shear (cemented to specimen)

[illegible] - stress due to bending moment

[illegible] - stress due to axial force

[illegible] - dynamic force output measured with a PCB transducer

[illegible] - response was negligible